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# Sustainable structural intervention methodology for vulnerable buildings from a lifecycle perspective

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**Abstract.** The frequency of disasters recorded around the globe, combined with inadequate enforcement of design codes, the natural deterioration of the existing built fabric and poor use of land due to rapid urbanisation make urban infrastructure vulnerable to experience damage. This eventually creates the need for building retrofitting, which triggers further environmental degradation. Furthermore, the lack of a well-defined approach to guarantee sustainable structural recovery derives on structural interventions focusing on strengthening elements to improve their performance only, hence ignoring the plethora of building deficiencies associated to post-disaster retrofit. The aim of this investigation is therefore to embed structural upgrading within the principles of sustainability while developing the metrics to enable structural damage reduction. This will contribute to optimising post-disaster building interventions. The proposed approach is applied to a pilot case to illustrate identified alternatives for improving the performance of otherwise vulnerable infrastructure from a life-cycle perspective.

## 1. Introduction

Historical data show that human and material loss induced by natural events such as wind and earthquakes grow exponentially. Just over the past decade, the number of disasters that occurred between 1970 and 1979 quadrupled [1]. As the occurrence of natural disasters cannot be reduced, increasing structural resilience stands as a viable alternative for reducing disaster risks in vulnerable buildings.

In recent years, there has been an upward trend in retrofitting approaches aimed at energy retrofitting for reducing emissions mainly caused by heating and cooling devices. According to [2], 1.2% of the EU's building stock is renovated every year for reducing the energy consumption, however this situation is insufficient when considering that three-quarters of the EU's existing building stock is expected to be in use until 2050. Furthermore, energy investments for existing buildings can be wasted by hazard risks because of the structural vulnerability in the seismic prone areas [3]. Figure 1 shows some examples of energy investments that failed once safety of these buildings was ignored during the implementation of such mechanisms [4]. This seems a concurrent pattern of engineering practice that aims at improving one aspects of building performance only, hence ignoring their interrelation with other building deficiencies [5]. The two cases shown in Figure 1 illustrate how energy consumption infrastructure developed independently from building operation and management as well as to seismic risk. This evidences the fact that human safety should be overseen during energy or other type of retrofit [5], [6]. Therefore, structural strengthening methodologies for renewing the building stock need further scrutiny to synchronise with sustainable developments that strive to modernise construction practices.





a. Roof collapse of a library building in Italy for gravity loads, in 2015.



b. Roof collapse of a building in Italy after Emilia earthquake in 2012.

**Figure 1.** Failed energy investments made on vulnerable buildings [4].

Based on the above facts, some initiatives to combine seismic retrofitting techniques with environmental considerations have emerged for a more robust criterion to upgrading building performance [7], [8]. This is accompanied with upgraded environmental criteria for setting up the sustainable rating systems that are now in use [9]. In addition to that, to mitigate emissions, researchers are embedding safety aspects with sustainable energy consumption practices into energy retrofitting techniques [6], [10], such as through the use of exoskeleton that allows more control on thermal and operational energy optimization [2],[6],[11],[12],[13]. The facts underpinning forward-looking retrofitting processes are as follows. During the manufacturing, construction, repair and demolition of a vulnerable building, large amounts of CO<sub>2</sub> emissions tend to occur. This embodied carbon can constitute up to 10-20% of the total carbon footprint of a building from cradle to grave [9], which can directly impact human health as toxic emissions also occur [3], [5]. However, currently most techniques aim at reducing the operational energy to nearly zero while excluding embodied. These environmental impacts are progressively helping current environmental performance assessment methods to coming into effect when comparing building solutions, noting that structural performance was not originally embedded in those assessment methods [14]. This highlights the lack of well-defined systematic approaches and methods to incorporate procedures to deal with disaster damage into sustainability metrics [15]. Better integrated methodologies are thus required to reduce disaster risk and to optimise structural interventions.

The aim of this research is to further scrutinise the concept of structural resilience while revisiting key sustainability metrics with the purpose of enhancing these for the benefit of building interventions. The proposed methodology builds on two criteria depending on the scale of the damage inflicted to infrastructure. This derives into three posterior stages for evaluation that cover the remaining life of buildings.

This research promotes structural retrofit to be seen as a set of actions to reducing structural vulnerability of buildings as well as the associated environmental footprint. The sustainable intervention also directed to reducing economic and social disruption through well-designed actions to prevent disasters.

## 2. An integrated method on sustainable structural intervention

In this paper, vulnerable buildings are described as buildings susceptible to damage derived from natural hazard, poor design and construction, deterioration of constituent materials, lack of maintenance and unplanned urbanisation.

These factors would prevent infrastructure from meeting pre-determined performance objectives. It is acknowledged that strengthening procedures and techniques are subject to local practices, therefore, the sustainable performance of buildings is to some extent subject to interpretation. Notwithstanding that, widely disseminated methodologies such as Sustainable Structural Design (SSD), which combines EU standards and sustainability [16],[17] and FEMA P-58-4, which combines FEMA P-58 and environmental impacts [18], support uniformisation of criteria across countries. These integrate sustainability into specific methodologies for assessing the seismic performance of buildings and intend

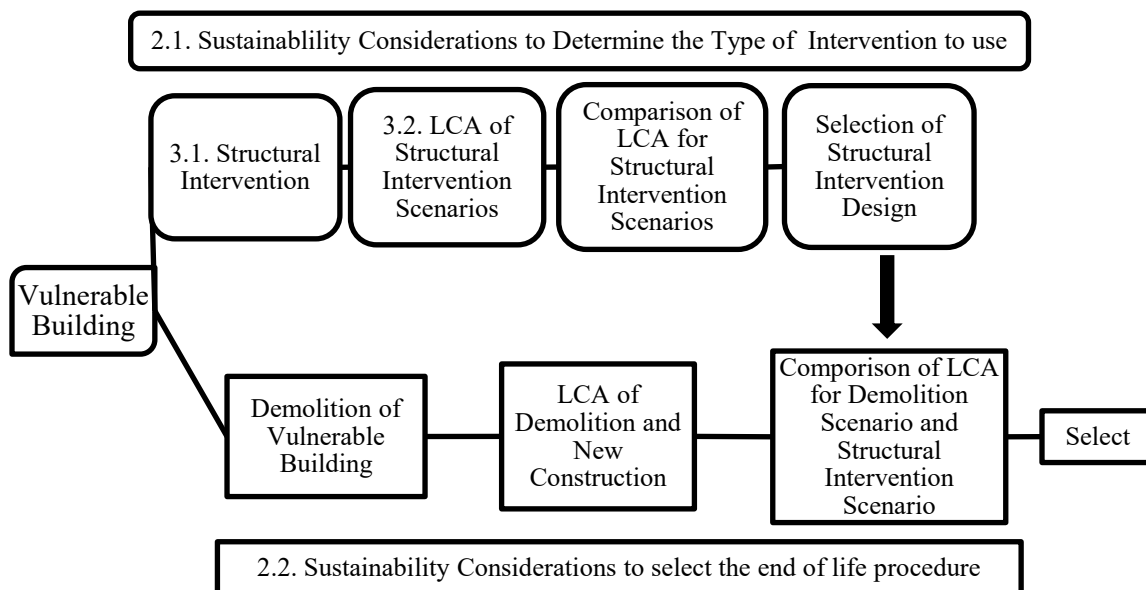
to make them specific according to the target region [14]. As we know, building performance objectives may vary with the selected performance level, or conversely, performance-based standards may target different objectives [19]. In this study, a sustainable structural intervention methodology is developed bearing in mind the referred variability of local practices.

The methodology discussed herein therefore depicts structural intervention as an integrated process that fits sustainability existing frameworks. In this context, life cycle assessment (LCA) stands as the main vehicle to assess retrofitting impacts under the following criteria,

1. *Sustainability considerations to determine the type of intervention to use.*
2. *Sustainability considerations to select the end of life procedure.*

Interventions are expected to extend building's service life, hence the extended service life need to be taken into account in the life cycle analysis [18]. To build on this idea, these two criteria developed considering the different impacts of selected scenarios on building life and environment. The first one is to exploring retrofitting alternatives that fulfill sustainability best practice. In the case of demolition, end of life procedures (second criteria) become relevant, because this situation is reversed due to the long service life of the new building. Therefore, annual environmental impacts for end of life procedure can be considered [18]. Either path, will require progressive environmental impacts to ensure each link in the chain addresses sustainability goals. In line with it, the current framework incorporates periodic three posterior stages environmental impact assessments to be carried out.

These two criteria define the two-stage process shown in Figure 2, while each criterion is discussed in sections, 2.1 and 2.2, respectively.



**Figure 2.** Outline of the proposed methodology.

### 2.1. Sustainability considerations to define the type of intervention to use

Recently due to construction of buildings in compliance with the building regulations, the occurrence of moderate or low damaged buildings became more frequent after disasters, which results in a single decision, such as structural intervention. The development of construction technology has enabled various strengthening techniques to be narrowed down during planning. The preliminary selection can then progress to standard life cycle analysis. This process excludes as-built materials and operational impacts because these are not changing through intervention works. After, assessment is made to compare environmental impacts of intervention scenarios through building's processes.

## *2.2. Sustainability considerations to select the end of life procedure*

Demolition is perhaps the most common end of vulnerable buildings, especially for those whose constituent materials stand as heavily damaged or deteriorated. The proposed framework now includes the assessment of building's sustainable performance, including the end of life adopted method. The assessment process should include a qualitative evaluation of alternatives such as demolition versus maintenance and/or retrofit - bearing in mind the extended life service provided by the latter. It thus seems convenient to discretise the environmental assessment of buildings into annual impact assessments [18].

## **3. The proposed methodology for sustainable structural interventions**

The methodology prioritises ways to measuring the environmental benefits of structural retrofit. More broadly, it aims at embedding retrofit impacts into the standard life cycle assessment. Those are the two-stage process that would yield sustainable interventions.

### *3.1. Structural intervention of damaged buildings*

The layout of this section is purposefully general so that it aligns with existing research that proposes generalisation, i.e. design frameworks that can be used for any type of building, any local performance code, and any type of disaster inducing damage.

The process includes 3 stages (adapted from FEMA 356 [20] and BS EN 1998-3 [21]);

- *Obtaining As-Built Information of the Damaged Building*
- *Assessment of Building's Structural Capacity*
- *Selection of Structural Intervention and its Design*

*3.1.1. Obtaining as-built information of the damaged building.* It is necessary to understand the stability and robustness of the building. Dimensions and details of structural elements, the material properties, system's geometry, use of the facility including any changes of it over time, intended service life, geographic location and soil characteristics, will provide the key elements to progressing into the second stage, while their accuracy should be cross-checked against the original drawings, if available. The level of damage should be investigated and documented. The later could take the form of a visual inspection to identify structural damage. Destructive and/or non-destructive tests of a sample of materials should be conducted [20]. The careful scrutiny of the material collected could inform engineers about the level and severity of the damage while a portion of it could feed into posterior stages of damage evaluation.

*3.1.2. Assessment of building's structural capacity.* The assessment procedure should link safety with performance criteria as specified in the relevant code of practice [22]. The information collected in the previous stage should inform the modelling of the structure. The analysis of that model should yield details on internal forces and deformation of members as well as on global performance indicators such as whether sections exhibit elastic or inelastic behaviour e.g. to accurately determine their capacity level. Code procedures for strengthening of buildings should also be looked at to conform a reliable assessment of the building's capacity.

*3.1.3. Selection of structural intervention and its design.* The selection of the type of intervention is directly related to the initial rigidity, geometry and structural irregularities, if any, of the vulnerable building [6]. The assessment results is therefore to inform the selection of the type of intervention that could possibly help to limit structural performance to acceptable limits and desirably improve the performance level. The result of retrofitting should be capable to go through similar or higher loads than those that caused the damage, without collapsing while ensuring that the building meets the minimum sustainability performance targets as defined in the corresponding regulations.

The structural intervention can take the form of repair and/or strengthening. The former is executed to recover the building element's load-bearing capacity without upgrading structural resistance, while

the latter implies increasing the load-bearing capacity and upgrading structural resistance [23]. In this study, either repair or strengthening are referred to as intervention.

The classic forms of strengthening and/or modifying structural ductility of vulnerable buildings occur at local and global level [5]. Local interventions aim at increasing ductility, resistance, and stiffness of structural elements and joints [2], whereas global interventions aim at increasing the lateral stiffness of the overall system for example through the addition of structural elements like bracing and or shear walls [5].

All the intervention techniques have their own specific installation process and timescales. To make these sustainable interventions, the following aspects would ideally feed into the analysis of environmental impact [23]: structural safety, implementation technique, quality of workmanship, level of integration with other parts or components of the structure, noise and vibrations induced, cost, aesthetics, time, and investigation of users' satisfaction. In some cases, it might be difficult to combine or keep control on all these aspects, i.e. optimising partial procedures.

### 3.2 Incorporating structural intervention in the lifecycle assessment

The importance given to environmental protection has increased with the increase of environmental concerns, and the methods in this field have also developed with this interest [24]. One of the methods developed to better understand and address environmental impacts or burdens is the Life Cycle Assessment (LCA) [24]. Accordingly, significant works are being carried out through ISO, CEN and ASM to develop LCA methods [18].

General guidelines of LCA were issued by the ISO 14040 and ISO 14044, forming a comprehensive, structured and internationally standardised method [25]. This method aims at identifying environmental performance of buildings and materials throughout their life span [18]. LCA could also feed into decision-making processes to promote sustainability in the construction sector for addressing environmental concerns [26]. In recent years, existing methodologies, databases and tools related to LCA have been under continuously development and renovation [4]. As a result of that process, ISO 14044 [27] and ISO 14040 [24] now frame LCA into the following four steps, which are described in detail in the ILCD Handbook [25]:

- *Goal and Scope*: Goal is the reason of the study. Scope is including the system, system boundary, impact categories, quality of data, assessment parameters (data sources) and functions of the system. System boundary is limits in the process of life cycle.
- *Life Cycle Inventory Analysis (LCIA)*: Data (inputs) and their relevant impacts (output) are identified.
- *Life Cycle Impacts Assessment (LCIAs)*: Life cycle impact results are calculated.
- *Interpretation*: Discussions, comparisons, decision-making and recommendations are made based on assessment results underpinned by the Goal and Scope.

To harmonise structural interventions and LCA, it is necessary to recall the framework represented in Figure 2 and detail the two-stage process. Once the viable types of structural interventions are selected, as per section 3, the corresponding life cycle assessments can be carried out. That could be achieved either as unit process economic input-output (EIO), or hybrid process. The unit process is a traditional and arguably the most precise approach [18]. Since the present study is based on bills-of-materials, the unit process is adopted to complete the inventory.

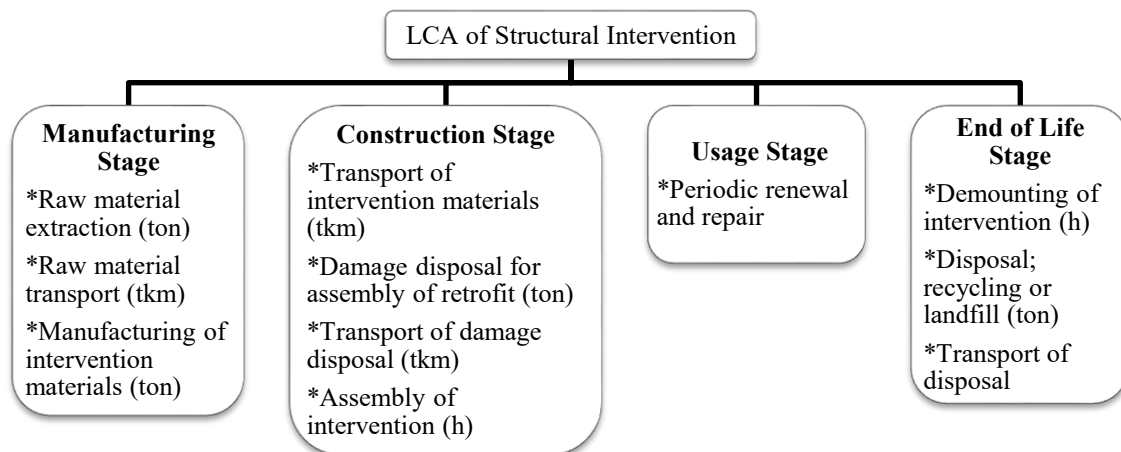
LCA stages are constrained by system boundaries as cradle-to-grave in ISO 14040, however the details in the system boundaries shaped with the goal of the study [24]. EN 15978 [28] presents specific LCA stages regarding building components and construction. However, for vulnerable buildings, those stages need further scrutiny to cover specific conditions of risk. Life cycle impacts related to disaster damages can be added to the basic LCA impacts of building construction and can be assessed separately with appropriate stages [18]. In this way, separate requirements derived from interventions can become part of an integrated approach [29]. For this reason, LCA stages for structural interventions should stand alone hence allowing space for proper reflection of damages associated to post disaster analysis. This is reflected in Figure 3 where structural intervention branches out into a specific parameterisation spanning

between raw material extraction and the end-of-life. Three posterior stages of the remaining lifecycle of the building are derived from these privatised LCA stages.

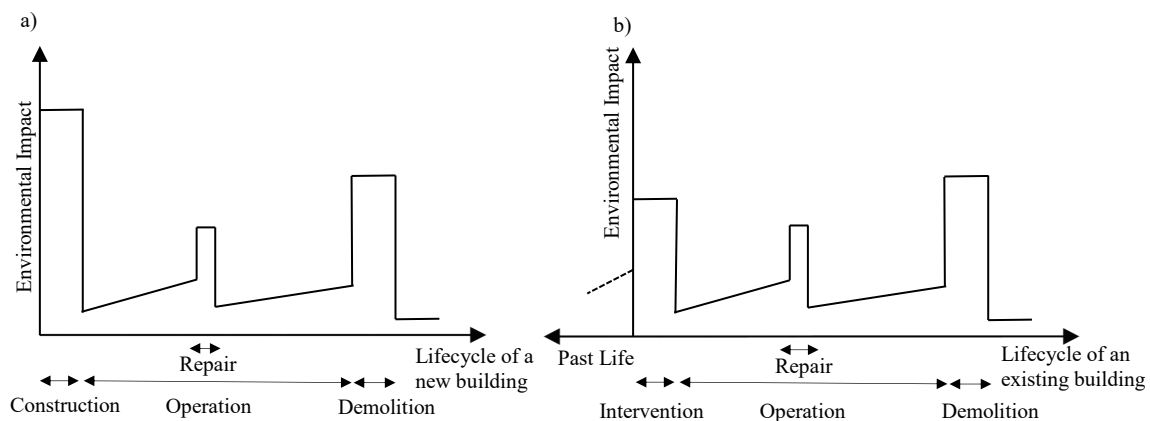
The objective of the proposed methodology is therefore to acknowledge the implications of decisions made during the planning, design and implementation of structural intervention with a sustainability perspective. The lifecycle assessment (LCA) can then inform evidence based decision-making processes [18]. The sustainable design decision made in this way would have met both sustainability and structural safety requirements.

#### 4. An overview of possible sustainable solution for vulnerable buildings

The rate of the embodied and operational environmental impacts of buildings is rapidly changing recently because of the crucial developments in the energy improvements for more operationally efficient buildings [18]. Therefore, this effort tends to develop towards a reduction of embodied energy and relevant environmental impacts of buildings [30]. In this context, preserving the building stock is preferred to avoid generating new construction processes where most embodied emissions tend to occur. This is illustrated in Figure 4, which compares the environmental impacts of new building and retrofitted buildings. Figure 4 also highlights the extended environmental impact analysis associated to the retrofit [31]. In that graph, the segment of the curves associated to construction and demolition are flat. The opposite is true for the operational stage showing a fluctuation occurring.



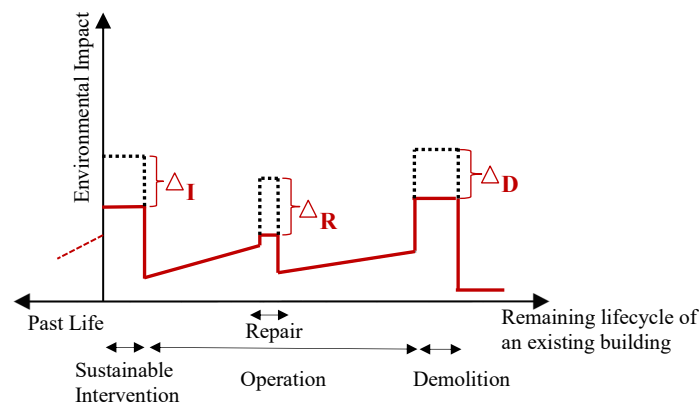
**Figure 3.** Lifecycle of a structural intervention.



**Figure 4.** Environmental impacts of a) new building through its complete lifecycle, and b) existing building through its remaining lifecycle [31].



The environmental impacts caused by intervention, repair and demolition periods (as seen in the Fig. 4.) can be reduced by implementing sustainable interventions. In light of the framework discussed above, the effect of optimised structural interventions is depicted in Figure 5. In those terms, the vulnerability of the existing building stock to undesirable natural disasters to come is considered. Hence, the strengthening of buildings to optimise the cost-benefit relationship requires further attention and further investigation.



**Figure 5.** Environmental impact of a sustainable structural intervention ( $\Delta_I$ ,  $\Delta_R$ ,  $\Delta_D$ ; estimated rate of change (benefit) for intervention, repair and demolition, respectively.).

## 5. Case Study

The proposed methodology is now applied to a retrofit solution departing from two potential scenarios. This refers to a reinforced concrete building located in Turkey. The building (shown in Fig. 6.) was damaged due to consecutive earthquakes that occurred in Van, 2011. To assess the structural performance of the damaged building, several steps had gone through using as-built information, then modelling the structure to assess its structural capacity according to the Turkish earthquake code, and finally appropriate intervention scenarios were selected to improve the performance level of the building. The local interventions took the form of structural retrofit, as seen in Fig.6. Two intervention scenarios were scrutinised: (i) reinforced concrete (RC) jacketing and RC beam replacement and (ii) steel jacketing and steel beam replacement.

In the present study, environmental performance analysis derived from the manufacturing of materials, damage disposal and their transportation (intervention stage), repair, and waste treatment/disposal and transportation (demolition stage) of two scenarios, was carried out using OpenLCA [32]. The carbon emissions (kg CO<sub>2</sub>) and air emissions (kg SO<sub>2</sub>) as embodied environmental impacts were exported. Then, the impacts of each intervention scenario for each stage are presented and compared in table 1.

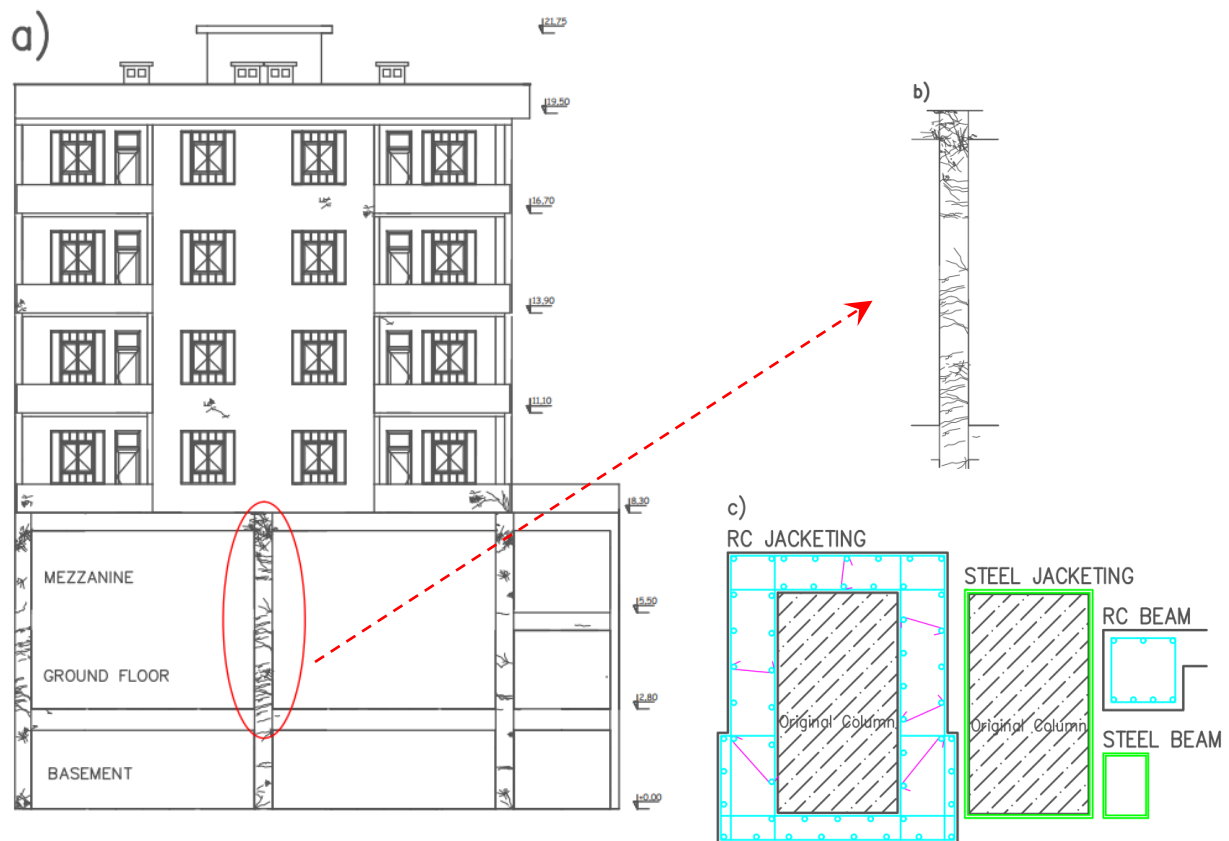
**Table 1.** Lifecycle environmental impacts of intervention scenarios.

Impact Category	1.Scenario			2.Scenario			$\Delta_I$	$\Delta_R$	$\Delta_D$
	RC Intervention	RC Repair	RC Demolition	Steel Intervention	Steel Repair	Steel Demolition			
Acidification potential <sup>a</sup>	2.78E+03	6.82E+00	-1.73E+02	6.65E+02	2.21E-01	-3.16E+01	61% ↓	94% ↓	69% ↓
Climate change <sup>b</sup>	5.66E+05	2.64E+03	-3.49E+04	1.50E+05	8.55E+01	-6.37E+03	58% ↓	94% ↓	69% ↓

Depletion of abiotic resources <sup>c</sup>	3.72E-01	2.93E-03	-2.36E-02	-1.81E-01	9.50E-05	-4.32E-03	34%↓	94%↓	69%↓
Human toxicity <sup>d</sup>	3.34E+04	1.68E+02	-2.08E+03	8.40E+03	5.44E+00	-3.80E+02	60%↓	94%↓	69%↓

<sup>a</sup> kg SO<sub>2</sub> equivalent  
<sup>b</sup> kg CO<sub>2</sub> equivalent  
<sup>c</sup> kg antimony  
<sup>d</sup> kg 1,4-dichlorobenzene

As a result, the RC jacketing is the scenario with the biggest share in environmental impacts for all the life cycle stages. Therefore,  $\Delta$  values were calculated by subtracting the RC-jacketing results from steel-base results to find out the contribution of sustainable solutions for structural interventions. The highest decrease is seen in the repairing stage, followed by the demolition and intervention stages.



**Figure 6.** Vulnerable reinforced concrete building and its structural intervention scenarios.

## 6. Conclusion

The proposed method presents an approach for assessing the lifecycle environmental impact of structural interventions for vulnerable buildings. For a pilot case, two different intervention scenarios were computationally assessed for their embodied environmental impacts over the entire lifecycle. The assessment helped to determine which structural intervention scenario minimises environmental impacts. It was found that steel jacketing has lower environmental impact than RC jacketing.

This research emphasises the possibility of sustainable structural interventions that can reduce structural vulnerability of buildings alongside the environmental footprint. The applied technique points towards optimised solutions when selecting structural strengthening techniques for a damaged building.

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